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Measurement of the relative intensity of the Ly-α lines in Fe^{25+}

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The intensity of the polarized Ly-α_1 ($2p_{3/2} \rightarrow 1s_{1/2}$) transition has been measured relative to that of the unpolarized Ly-α_2 ($2p_{1/2} \rightarrow 1s_{1/2}$) transition in Fe^{25+}. The measurements were made with the Livermore electron beam ion trap EBIT-II for beam energies from threshold to 2.5 times threshold. The results are compared to the corresponding intensity ratio predicted using excitation cross sections from distorted-wave calculations, which includes polarization, the M1 ($2s_{1/2} \rightarrow 1s_{1/2}$) transition, and cascade contributions. Discrepancies are found that tend to confirm recent a recent report of a measurement of the Ly-α lines in Ti^{21+} performed on the Tokyo electron beam ion trap.

I. INTRODUCTION

X-ray polarization is predicted to occur whenever ions collide with non-Maxwellian electron velocity distributions. It has been used as a diagnostic to study bremsstrahlung from a vacuum spark plasma [1], laser-produced plasmas [2], and solar flares [3–6]. Of particular interest has been the ratio of Ly-α_2 ($2p_{1/2} \rightarrow 1s_{1/2}$) and Ly-$\alpha_1$ ($2p_{3/2} \rightarrow 1s_{1/2}$), which is labeled "$B$" by solar physicists [7]. The reason is that this ratio is thought to be well understood and essentially constant as a function of electron temperature. Moreover, one of the two lines, Ly-α_2, is always unpolarized. Hence deviations from the predicted ratio of B is taken as evidence for polarization of Ly-α_1, and thus for the excitation of the ions by electrons in a beam.

A very recent measurement of B in Ti^{21+} was reported by Nakamura et al. [8]. The measurement was performed on the Tokyo electron beam ion trap facility. It showed that B did not agree with predictions even if polarization effects are taken into account. This was taken to be evidence that the calculated polarization values are inconsistent with the experiment by as much as 50%, casting doubt on the accuracy of the calculations.

In this paper we present a measurement of the Ly-α_2 transition relative to the Ly-α_1

transition in hydrogenlike iron using the Livermore EBIT-II electron beam ion trap. We show that B disagrees in a similar way from theory as the Tokyo result, albeit to a smaller extent if radiative cascades are properly taken into account.

II. POLARIZATION EFFECTS

Polarization has two effects on the x rays we measure: (1) since we measure x rays at 90° to the electron beam our detectors and spectrometers are sensitive to the angular distribution of the x rays, and (2) our crystal spectrometer acts as a polarimeter, which preferentially detects x rays polarized perpendicular to the plane of dispersion.

For electric dipole radiation, i.e., the primary type we study in this paper, the expression for the x-ray intensity at 90°, I(90°), and the average over the 4π solid angle, $\langle I \rangle$, is [9]

$$I(90^\circ) = \frac{3}{3-P}\langle I \rangle. \tag{1}$$

P is defined as the linear polarization and is given by

$$P = \frac{I_{||} - I_{\perp}}{I_{||} + I_{\perp}}, \tag{2}$$

where $I_{||}$ and $I_{\perp}$ are the intensities of the x-ray emission components with electric field vectors parallel and perpendicular electron beam, respectively, and

$$I_{||} + I_{\perp} = I(90^\circ). \tag{3}$$

The x-ray intensity $I^{\rm meas}$ measured with our crystal spectrometer is

$$I^{\rm meas} = R_{||} I_{||} + R_{\perp} I_{\perp}, \tag{4}$$

where $R_{||}$ and $R_{\perp}$ are the integrated reflectivities of the crystal for x rays polarized parallel and perpendicular to the electron beam, which were provided by Gullikson [10].

Combining Eqs. (1)-(4), the intensity ratio we measure for two electric dipole x-ray lines is related to their 4π average by the expression

$$\frac{I_1^{\rm meas}}{I_2^{\rm meas}} = \frac{W_1 \langle I_1 \rangle}{W_2 \langle I_2 \rangle}, \tag{5}$$

where we define W to be

$$\frac{W_1}{W_2} = \frac{R_1(P)A_1(P)}{R_2(P)A_2(P)} = \left(\frac{(1+P_1) + \frac{R_\perp^1}{R_{||}^1}(1-P_1)}{(1+P_2) + \frac{R_\perp^2}{R_{||}^2}(1-P_2)} \right) \left(\frac{3-P_2}{3-P_1} \right), \tag{6}$$

The terms $R(P)$ and $A(P)$ represent the reflectivity and angular distribution terms, repectively. The values for $\frac{R_\perp}{R_\parallel}$ are less than 1. Therefore, positive polarization enhances and negative polarization decreases the intensity of an x-ray line relative to an unpolarized line.

III. EXPERIMENT

EBIT-II consists of a series of three drift tubes [11,12]. It uses an electron beam ($\leq$ 150 mA) to generate, trap, and excite highly charged ions. Low charged ions are injected into the trap from the MeVVA ion source [13], while gases are ballistically injected through the side ports. The ions are trapped radially by the electron beam that is compressed to a radius of roughly 30-μm by a 3-Tesla magnet. They are trapped axially by the two end drift tubes, which are biased positive with respect to the center drift tube.

The x rays generated by the electron-ion collisions are recorded with EBIT-II's curved crystal Bragg spectrometer in the von Hámos geometry [14]. In our experiment we used a LiF(200) crystal with a lattice spacing of 2d = 4.027 Å. The crystal was bent to a radius of curvature of 30 cm. The resolving power of the setup is $\Delta\lambda/\lambda \approx 1500$. The spectrometer was set to a nominal Bragg angle of 26.8° which corresponds to a wavelength of 1.81 Å. The total wavelength covered was 1.77 Å $< \lambda <$ 1.88 Å which contains the hydrogenlike transitions Ly-α_1 ($2p_{3/2} \rightarrow 1s_{1/2}$) at 1.7780 Å and Ly-$\alpha_2$ ($2p_{1/2} \rightarrow 1s_{1/2}$) at 1.7834 Å [15]. A typical x-ray spectrum taken with the electron beam energy set to 15 keV is shown in Fig. 1.

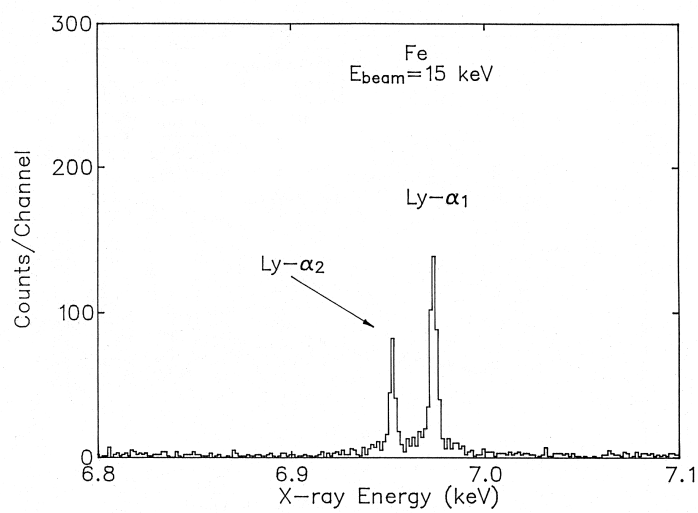

FIG. 1. Direct excitation x-ray spectrum of Fe^{25+} measured with a Bragg crystal spectrometer at an electron beam energy of 15 keV showing Ly-α_1 and Ly-α_2.

The Ly-α_2 intensity has a contribution from an M1 ($2s_{1/2}\rightarrow 1s_{1/2}$) transition, which cannot be resolved from the Ly-α_2 x ray. The separation between the two transitions in iron is a mere 0.03 eV. The $2s_{1/2}$ upper level decays 10% of the time by M1 (magnetic dipole) radiation and 90% of the time by two photon decays [16]. Therefore, the M1 transition results in an x ray which blends with and adds to the effective intensity of Ly-α_2.

We have measured Ly-α_2 and Ly-α_1 in iron as a function of electron beam energy for energies near the excitation threshold of Ly-α_1 at 7.1 keV to 18 keV. The measurements for energies from 10 to 18 keV were made in steady-state at one beam energy, and recording a spectrum of approximately 250 counts in Ly-α_2 and 500 counts in Ly-α_1 typically lasted 50 min. However, the measurements made below 8.828 keV, which is the ionization potential for producing hydrogenlike iron, are made by taking advantage of electron beam ion trap's ability to alternate the electron beam accelerating voltage (5 kV/ms) from one value to another and back. This feature allows us to create the ionization balance at, e.g., 15 keV and to probe the hydrogenlike transitions at energies below 8.828 keV. These spectra took roughly 6 hours each to acquire. The excitation energies of Ly-α_2 and Ly-α_1 in iron are 6.952 keV and 6.973 keV, repectively.

We compare the experimental intensities of Ly-α_2 and Ly-α_1 with those predicted at 90° to the electron beam direction. For Ly-α_2 and Ly-α_1, the predicted x-ray intensities are:

$$I_{\mathrm{Ly}-\alpha 2} = \frac{j_e}{e}(\sigma_{\mathrm{Ly}-\alpha 2} + 0.1\sigma_{\mathrm{M1}})n_{\mathrm{H}}W_{\mathrm{Ly}-\alpha 2}G, \tag{7}$$

$$I_{\mathrm{Ly}-\alpha 1} = \frac{j_e}{e}\sigma_{\mathrm{Ly}-\alpha 1}n_{\mathrm{H}}W_{\mathrm{Ly}-\alpha 1}G, \tag{8}$$

where j_e is the effective current density, e is the charge of the electron, $\sigma_{\mathrm{Ly}-\alpha 2}$, σ_{M1}, and $\sigma_{\mathrm{Ly}-\alpha 1}$ are excitation cross sections calculated with the distorted-wave code of Zhang et al. [17], n_{H} is the number densities of ground-state hydrogenlike ions, and G is the solid angle subtended by the spectrometer. W, which we derived in the last section, accounts for the angular distribution of the x rays, their linear polarization, and the reflectivity of the LiF(200) crystal. P=0 for Ly-α_2 plus the M1 contribution (J=1/2→1/2 transitions). The polarization for Ly-α_1 is given by:

$$P = \frac{3(N_{1/2} - N_{3/2})}{3N_{3/2} + 5N_{1/2}}, \tag{9}$$

where $N_{1/2}$ and $N_{3/2}$ are the magnetic sublevel populations. This formula was derived by Inal and Dubau [18] for ions excited by an electron beam. It was derived for the lithiumlike line

q $(1s2s(^3S)2p\ ^2P_{3/2} \rightarrow 1s^22s\ ^2S_{1/2})$, which is analogous to Ly-α_1 for hydrogenlike ions, for x rays observed at 90° to the electron beam. Line q and Ly-α_1 are both E1 (elecric dipole), J=3/2→1/2 transitions. Because the magnetic sublevel populations are energy dependent, the theoretical value P for Ly-α_1 varies from 0.363 near the excitation threshold of the Ly-α lines at 7.025 keV to 0.250 at 20 keV; the corresponding variation of $W_{\mathrm{Ly}-\alpha 1}$ is from 1.99 to 1.86.

IV. RESULTS

The observed value of B, i.e., the ratio of Ly-α_2 to Ly-α_1, is shown in Fig. 2. The error bars shown reflect the uncertainties associated with determining the relative line intensities given that the two lines are not fully resolved in the observations because of the Lorenztian-shaped wings at the base of each line.

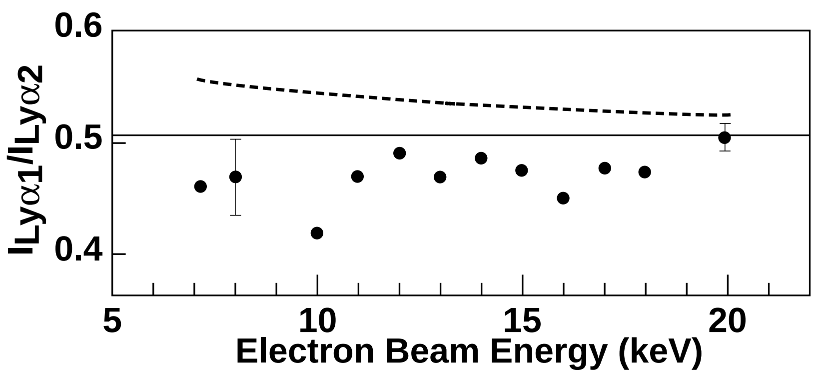

FIG. 2. Dependence of the measured Ly-α_2 to Ly-α_1 ratio on beam energy. Theoretical predictions based on direct electron-impact excitation with and without including the $2s \rightarrow 1s$ magnetic dipole transition are shown as dashed and solid lines, respectively. The predictions do not include polarization effects.

Also shown in Fig. 2 is the ratio of B that results from direct electron-impact excitation of the $2p_{1/2}$ and $2p_{3/2}$ of the $1s$ ground state. From statistical considerations, i.e., excitation to a $j = 3/2$ versus a $j = 1/2$ electron, we expect this ratio to be 0.50. It is slightly higher due to relativistic effects. No polarization effects are accounted for in this prediction. The theoretical ratio is even larger when adding the contribution of the unresolved $2s \rightarrow 1s$ magnetic dipole transition, which enhances the effective intensity of the Ly-α_2 line. Figure 2 shows that the measured value of B is clearly smaller than the predicted values without polarization.

In Fig. 3 we add polarization effects to the theoretical B ratio. The positive polarization of Ly-α_1 enhances the intensity relative to Ly-α_2 (and the $2srightarrow1s$ contribution) resulting in a smaller value of B. We calculated that B changes by only 4% when the reflectivity of the crystal, $\frac{R_\perp}{R_\parallel}$, is varied by 25% between the upper (0.675) and lower (0.525) limits. The value we use in the calculations is 0.606. The figure shows that now the measured values of B are larger than predicted.

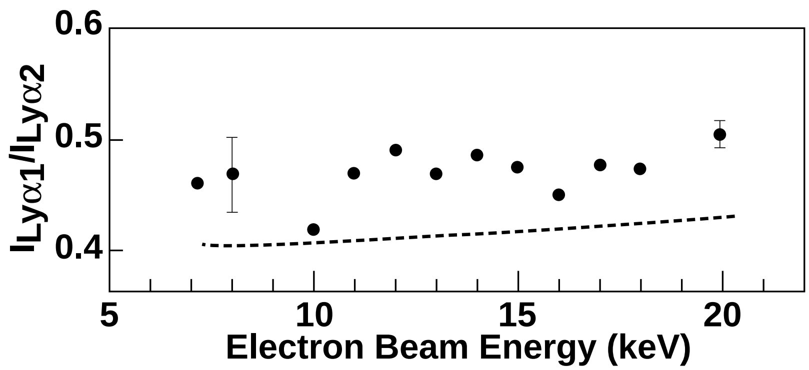

FIG. 3. Comparison of the measured Ly-α_2 to Ly-α_1 ratio with theoretical predictions based on direct electron-impact excitation, including the $2s \to 1s$ magnetic dipole transition, and polarization effects.

This is the same result Nakamura et al. [8] found in their analysis of the Lyman lines of Ti^{21+}. Clearly, if the polarization of Ly-α_1 was only two-thirds of the predicted values, the theoretical B ratios would have passed through the observations. This is exactly what Nakamura et al. [8] found.

This is however not the end of the story. The lines are not only excited by direct electron-impact collisions. They are also fed by radiative cascades and radiative recombination of beam electrons with bare ions. These effects were studied by Nakamura et al. and found not to change the results significantly. We agree that these effects do not significantly change the predicted unpolarized B value. However, radiative cascades have the effect of depolarizing Ly-α_1 by about 10We have included cascades from levels up to n=5. The primary cascade contributions to Ly-α_2 and Ly-α_1 come from the n=3 levels, while the M1 transition has contributions from n=2, 3, 4, and 5. For example, at an electron beam energy of 12.5 keV cascades are predicted to contribute 7%, 15.8%, and 6.3% to the observed intensity of Ly-α_2, M1, and Ly-α_1, respectively.

The comparison of the theoretical ratios including radiative cascades with the observations are shown in Fig. 4. The agreement between theory and measurement is improved, but still not perfect.

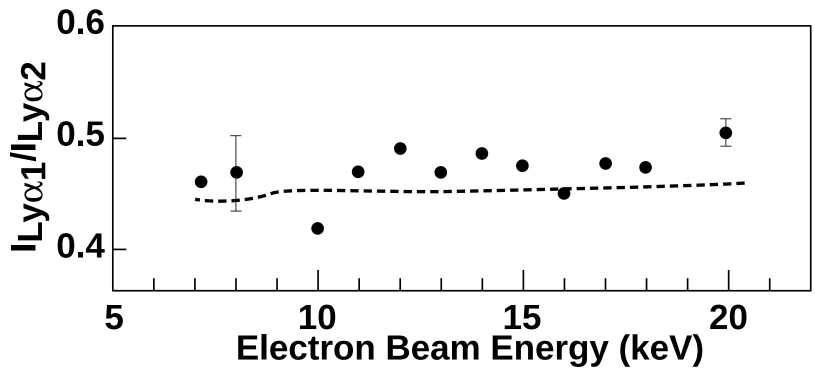

FIG. 4. Comparison of the measured Ly-α_2 to Ly-α_1 ratio with theoretical predictions based on direct electron-impact excitation, radiative cascades from levels $n \leq 5$, blending with the $2s \rightarrow 1s$ magnetic dipole transition, and polarization effects.

V. CONCLUSION

We have measured the ratio of Ly-α_2 and Ly-α_1 as a function of electron beam energy from threshold to 2.5 times threshold. The results are compared to theoretical predictions of B, which includes the polarization, the M1 contributions, and cascades. We find that the measured value of B is larger than predicted. If the polarization of Ly-α_1 was about 20 % less than predicted, good agreement would have been achieved. Our results that agree qualitatively with those obtained by Nakamura et al. [8], who studied the Lyman lines in hydrogenlike titanium.

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